Parameterization of Integrated Aerosol Effects in Marine Stratocumulus Clouds

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LONG-TERM GOALS

The development and improvement of cloud microphysical parameterizations for use in cloud and numerical weather prediction models

OBJECTIVES

Conduct detailed studies of marine stratocumulus cloud microphysical processes using a high-resolution large eddy simulation (LES) model with explicit microphysics. Achieve better understanding of interactions between microphysical, radiative and boundary layer thermodynamical processes in order to improve their formulation in numerical weather prediction models.

Towards this goal, we investigate:

1) The role of turbulence mixing and air recycling in drizzle formation

2) The methods for retrieval of cloud and drizzle parameters for use in initialization of numerical forecast models

APPROACH

The research is based on the CIMMS high-resolution LES model of marine boundary layer stratocumulus clouds with explicit formulation of aerosol and drop size-resolving microphysics. The LES simulations, as well as observations from field projects are used to study the role of recycling and turbulence mixing in drizzle formation. Simulations of observing systems, like Millimeter Wave Cloud Radar with Doppler capabilities, are used to develop algorithms for retrieval of cloud liquid water and drizzle flux for initialization of boundary layer stratocumulus in mesoscale prediction models.

WORK COMPLETED

The following tasks have been completed this year:

1. The new high resolution simulations have been performed and the trajectory ensemble model has been applied for analysis of about 120,000 air parcel trajectories. The mixing in precipitating and non-precipitating stratocumulus has been investigated and a new mechanism of drizzle initiation and growth has been proposed. The results are described in a JAS paper now in press.

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2. A model of an observing system simulating millimeter wave cloud radar with Doppler capabilities has been developed and applied for analysis of radar reflectivity and Doppler velocity return signals from stratocumulus clouds with different amounts of precipitation. Based on the analysis we have suggested new methods for retrieval of cloud and drizzle parameters.

RESULTS

1. The role of turbulence mixing and air recycling in drizzle formation

We continued the study of the effects of turbulence mixing on formation of cloud microstructure and production of drizzle in boundary layer stratocumulus by performing a new set of simulations with enhanced spatial resolution (up to 10 m in the vertical). The analysis of ensembles of 120,000 trajectories showed that in drizzling stratocumulus air parcels repeatedly cycle in the cloud for long periods of time and that in-cloud time-scales are insignificantly affected by the high frequency turbulence fluctuations. Long in-cloud residence times combined with the induced by turbulence spatial inhomogeneity of timescales leads to non-adiabatic mixing between “old” and “new” parcels.

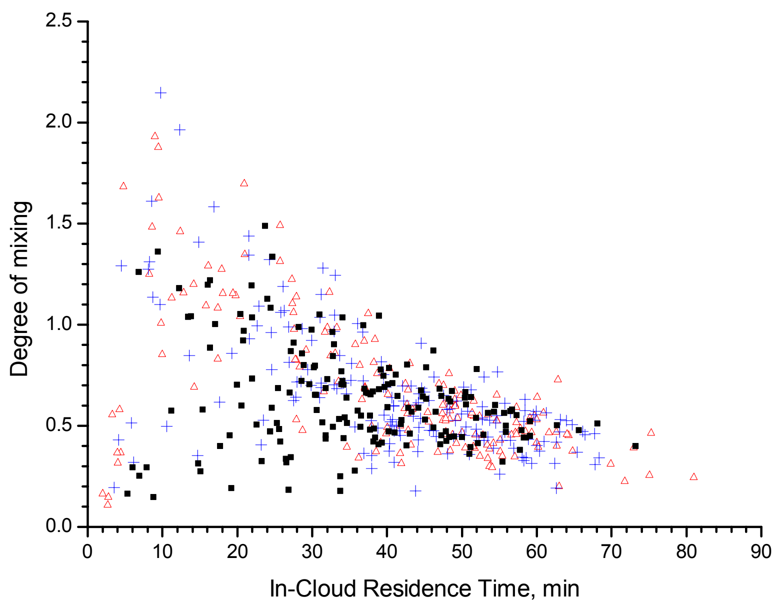

Figure 1. The degree of mixing in the cloud (the ratio of standard deviation of the residence time in an air volume to its mean value) shown at three cloud levels (bottom-red triangles, middle- blue pluses, top – black squares). [graph: The highest degree of mixing is in new parcels which have the smallest residence times]

Our experiments demonstrated that mixing of parcels with different histories, i.e., with drop size distributions at different stages of their evolution, provides embryos for coagulation in new parcels, contributes to drop spectral broadening and accelerates drizzle formation. The new parcels experience the highest degree of mixing (see Figure 1).

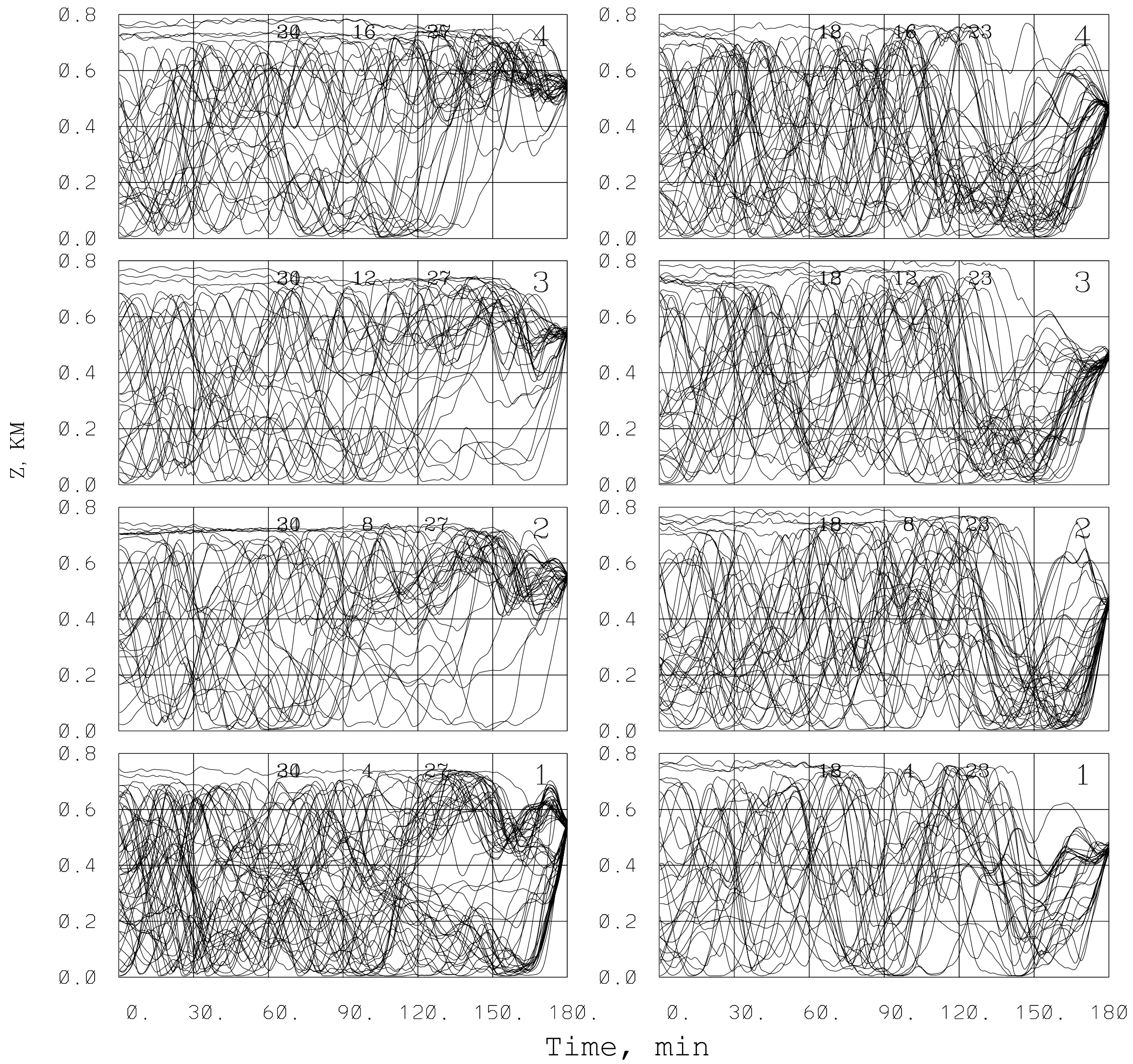

Figure 2. Air parcels height-time trajectories in selected air volumes in high resolution experiments under drizzling (left) and non-drizzling (right) conditions.
[graph: Air parcels spend more time in drizzling (left) than in non-drizzling Sc clouds]

The amount of time an air parcel resides in a cloud and, consequently, the degree of mixing depends on parameters which determine boundary layer flow circulation, in particular the predominant size and distribution of turbulent eddies. One of the key factors affecting boundary layer circulation is the presence of drizzle which results in the transition from a well mixed to a decoupled boundary layer. We contrasted simulations of drizzling and non-drizzling stratocumulus clouds. The drizzling case represented a decoupled boundary layer where the flow is dominated by eddies confined to the cloud layer. The in-cloud residence time of air parcels in this case is much larger than in the case of a non-drizzling, well-mixed boundary layer where prevailing eddies have characteristic size of the boundary layer depth and air parcels timescales, on average, are on the order of the large eddy turnover time. The comparison between left and right panels in Fig. 2 shows the effect of drizzle on air parcel trajectories. In the decoupled drizzling case there are more air parcels which are confined to the cloud layer, while the well-mixed non-drizzling case is dominated by large eddies of the size of the entire boundary layer. The difference is more apparent when less crowded panels are compared (e.g., #2 on

the left with #1 on the right). Our results also suggest an interesting mechanism of transition from non-drizzling to drizzling stratocumulus cloud. Mild evaporation of drops below cloud base in the initially non-drizzling cloud will lead early on to weak destabilization of the subcloud layer which, in turn, will result in the increase in the number of air parcels confined to the cloud layer. These parcels with long timescale trajectories will favor enhanced drizzle growth, which, in turn, will lead to stronger evaporation below cloud base followed by a stronger increase in stability of the subcloud layer and decoupling, all resulting in more air parcel cycling in cloud and more drizzle. The described positive feedback mechanism may eventually lead to stratocumulus cloud breakup.

2. The enhancement of radar retrievals by the use of higher moments of drop spectrum

We developed a model of an observing system simulating millimeter wave cloud radar with Doppler capabilities and applied it for analysis of radar reflectivity and Doppler velocity return signals from stratocumulus clouds with different amounts of precipitation. Measurements made during the Atlantic Stratocumulus Transition Experiment (ASTEX) field program in clean and polluted air masses were used to initialize the CIMMS large-eddy simulation model with size-resolving microphysics and to simulate cloud layers representing light (LD), moderate (MD) and heavy (HD) drizzle conditions. From each simulation we extracted about 5,000 drop size distributions (DSD), which were used to calculate cloud parameters, such as, e.g., drop concentration, liquid water content Q_l, precipitation flux R, radar reflectivity, Doppler velocity, etc. The set of DSDs, therefore, served as the source for deriving Q_l and R retrievals and as a benchmark for evaluating them by comparing with the exact values of Q_l and R. For stratocumulus clouds with negligible amount of drizzle, the retrieval of cloud liquid water is possible based on radar reflectivity alone and the parameters of the Q_l-Z relationship are in excellent agreement with the retrieval obtained using ASTEX observations by Fox and Illingworth (1997). When drizzle is present, Q_l is poorly retrieved based on Z alone; however the retrieval is substantially improved when information on Doppler velocity is included (Fig. 3). In clouds with substantial amounts of drizzle (R> 2mm/day) Z-R relationships can also be improved with information on drizzle mixing ratio or Doppler velocity. The retrieval of precipitation flux R in drizzling clouds using Z and $V_{d,}$ is more robust than retrieval of Q_l, obviously due to the fact that R, as well as Z and V_d, represents higher moments of the DSD (M_4, M_6, and the ratio M_7/M_6, respectively). Thus, strong correlation between them is expected, and this is indeed the case for MD and HD datasets. Fig. 4 shows a consistent increase in accuracy and reduction of scatter when V_d is included in the retrieval algorithm. The correlation is nearly perfect for the moderate drizzle case MD (R^2 = 0.997). For the heavy drizzle case HD R^2 increased from 0.794 for retrieval based on Z only to 0.962 when both Z and V_d are included. Our study strongly suggests that the velocity parameters collected by Doppler cloud radars should be incorporated in future retrievals of liquid water content and precipitation flux.

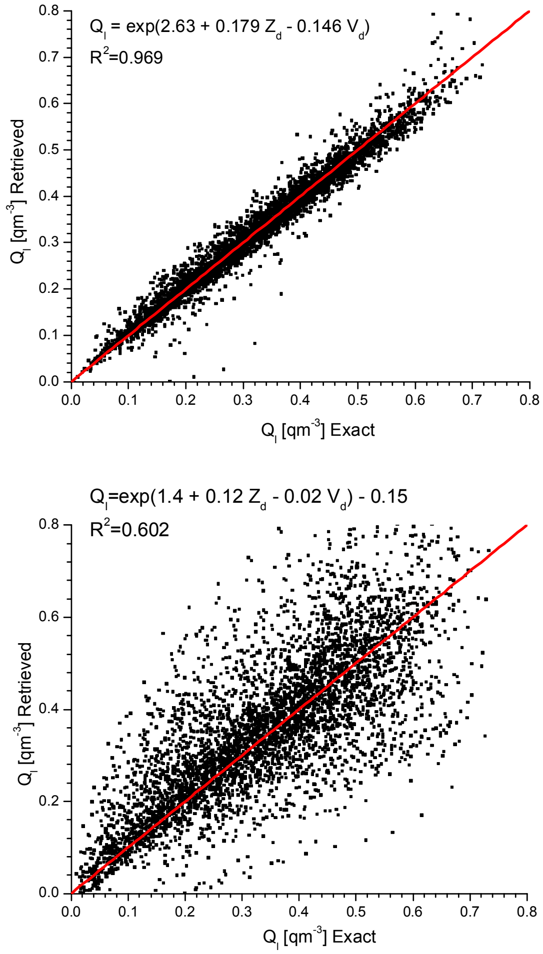

Figure 3. The retrieval of cloud liquid water as a function of reflectivity and Doppler velocity, (V_d). Top – the moderate drizzle case MD, bottom - the heavy drizzle case HD. Q_l in g m^{-3}, Z_d in dBZ, V_d in cm s^{-1}.
[graph: Accuracy of the liquid water retrieval is substantially improved with the inclusion of Doppler velocity parameter]

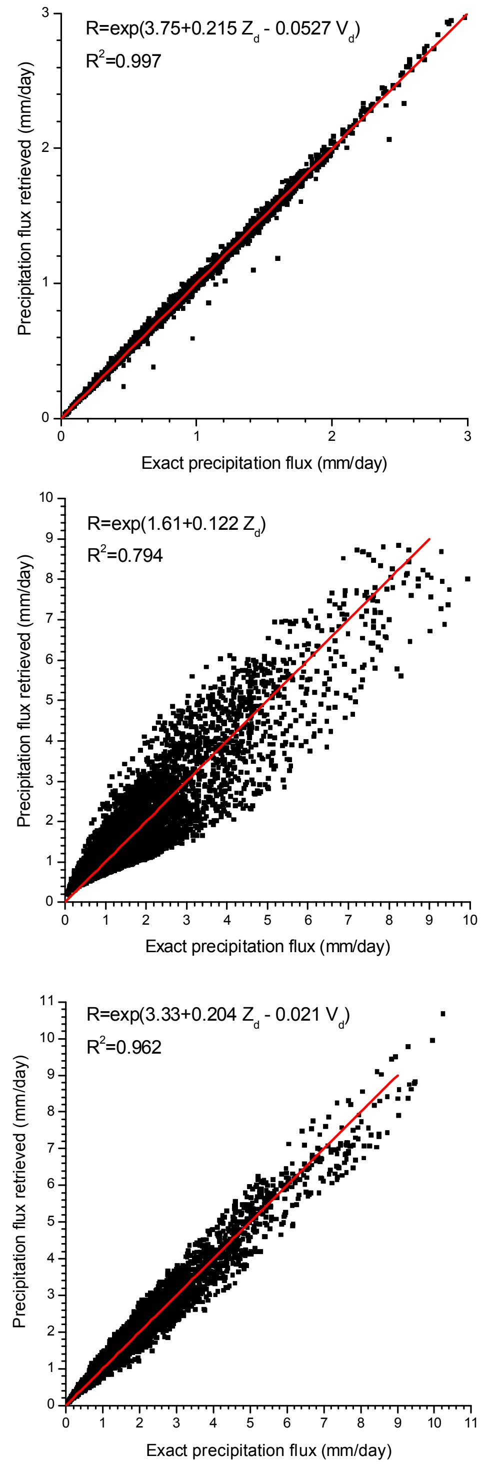

Figure 4. The retrieval of precipitation flux in cases with moderate (MD) (top panel) and heavy (HD) drizzle (middle and bottom). The middle panel shows retrieval as a function of reflectivity alone, the top and bottom - as a function of reflectivity and Doppler velocity, (V_d). [graph: Accuracy of precipitation flux retrieval is improved with the inclusion of Doppler velocity parameter]

IMPACT

The improved parameterization of the physical processes in marine stratocumulus clouds will lead to more accurate numerical weather predictions for Navy operations. The new retrieval algorithms of cloud and drizzle parameters will allow more accurate initialization of forecast models.

TRANSITIONS

Our results have been reported at three scientific meetings, published in two major refereed journals and conference proceedings (10 papers) and, thus, are known to the scientific community.

RELATED PROJECTS

The study is aimed at development of physical parameterizations for cloud and regional scale models. It is related to the ONR project "Improvement of the cloud physics formulation in the US Navy Coupled Ocean-Atmosphere Modeling Prediction System (COAMPS)" which goal is to implement physical parameterizations into mesoscale prediction models in general, and COAMPS in particular.

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